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$m = 1$ Diocotron Mode Damping in the Electron Diffusion Gauge (EDG) Experiment

Stephen F. Paul, Kyle A. Morrison, Ronald C. Davidson, Thomas G. Jenkins

Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08543, USA

Abstract. The evolution of the amplitude of the $m = 1$ diocotron mode is used to measure the background neutral pressure in the Electron Diffusion Gauge (EDG), a Malmberg-Penning trap. Below 5×10^{-8} Torr, the dependence on pressure scales as $P^{1/4}$, and is sensitive to pressure changes as small as $\Delta P = 5 \times 10^{-11}$ Torr. Previous studies on the EDG showed that the diocotron mode is more strongly damped at higher neutral pressures.Both the diocotron mode damping rate and the plasma expansion rate depend similarly on experimental parameters, i.e., conditions which favor expansion also favor suppression of the diocotron mode. The sensitivity of the mode evolution is examined as a function of the resistive growth driving conditions, which are controlled by the amount of wall resistance connected to the trap.

Nonneutral plasmas confined in Malmberg-Penning traps have been used to investigate important fundamental plasma phenomena [1, 2, 3]. For the Electron Diffusion Gauge (EDG) device at Princeton, the research program has emphasized examining the effects of collisions between the confined pure electron plasma and the background neutral gas as a means for determining the neutral gas pressure over a wide range. In recent theoretical work [4, 5], the expansion rate of a pure electron plasma was related to the rate of collisions between the electrons and the neutrals. The expansion rate has also been measured experimentally [6, 7], but these diagnostic techniques require repeated formation and termination of the plasma to determine the expansion rate. This approach is time-consuming and requires excellent reproducibility of the plasma conditions. At high pressures, the expansion rate is observed to scale classically [8], however the scatter in the data and the presence of asymmetry-induced expansion has limited the detection of neutral pressure in the EDG to $P > 10^{-8}$ Torr.

An alternative, non-destructive approach that does not require the determination of the entire density profile is the measurement of the growth and/or decay of the $m = 1$ diocotron mode. While the term "diocotron mode" was first used to describe instabilities in hollow nonneutral electron columns which have a shear in the angular flow velocity [9], in this paper it refers to low-frequency, electrostatic oscillations with azimuthal mode number $m = 1$. For small-amplitude perturbations, the physical interpretation of the mode is a plasma column, displaced from the central axis of the trap, that precesses at the diocotron mode frequency about the trap axis, defined as the center of symmetry of the cylinders that surround the plasma. The mode amplitude, A, is the distance from the center of the plasma column to the trap axis, and the growth/damping rate is defined as $(1/A) \times dA/dt$. As is typical in Malmberg-Penning traps, a uniform axial magnetic

field provides the radial confinement, and applied electric potentials on end cylinders provide axial confinement.

The co-linear, cylindrical copper trap electrodes have a wall radius of $R_w = 2.54$ cm, and the applied end potentials are typically -145V. The magnetic field is generated by a solenoid with an axial current profile adjusted so that the amplitude variation in the trap region is less than 0.2% of the total field, which may be varied from 300 to 600 G. The trap assembly is enclosed in an aluminum vacuum chamber and is pumped with a turbomolecular pump and a cryogenic pump to as low as 5×10^{-11} Torr. Helium gas is bled into the chamber with a precision metering valve and the fill pressure is measured with Bayard-Alpert ionization gauges located on either side of the trap. Details concerning the electron source and the method of trap operation have been described elsewhere [6].

The trapped electron plasma has an initial density in the range 8×10^6 cm^{-3} $< n <$ 3×10^7 cm^{-3}, temperature T of about 1-2 eV, radius $R_p \simeq 1.2$ cm, and length $L_p \simeq 15$ cm. For these parameters, the Debye length $(\lambda_D = (T/4\pi n e^2)^{1/2})$ is smaller than the diameter of the plasma $(R_p \simeq 6\lambda_D)$ and $\omega_{pe}^2/\omega_{cc}^2 < 0.01$, where $\omega_{pe} = (4\pi n e^2/m_e)^{1/2}$ is the electron plasma frequency and $\omega_{cc} = eB/m_e c$ is the electron cyclotron frequency. In thermal equilibrium, the $\mathbf{E} \times \mathbf{B}$ rotation frequency typically ranges from 10 kHz to 100 kHz. In a recent modification, the electron emitting filament was replaced one half as large. While the resulting plasma has half the initial radius of the previous plasmas, the line density, electric field, and diocotron frequency are approximately the same as before.

In the EDG experiment, one of the copper cylinders that surrounds the plasma is divided into two half-cylinders, so the mode amplitude is measured as an oscillating voltage induced by image charges on the half-cylinders by the precessing column [10]. Any odd-numbered diocotron mode $(m = 1, 3, \ldots)$ can be detected by adding a complex sensing impedance in series between either "half cylinder" and ground, but only the $m = 1$ mode has been investigated in these experiments.

CONTROLLING THE RESISTIVE GROWTH OF THE $m = 1$ DIOCOTRON MODE

In the absence of wall resistance or collisions with background neutrals, the $m = 1$ mode in an infinitely long plasma is predicted to be marginally stable regardless of the profile shape. However, given the finite sensing impedance that must be applied to record the diocotron mode amplitude, some amount of resistance must be present. Physically, a resistive wall dissipates the electrical potential energy of the plasma column, causing it to move nearer to the wall, i.e., the mode amplitude grows. For a plasma with a mono-tonically decreasing radial density profile, resistive-wall destabilization was predicted and experimentally verified by White [11].

In the EDG, resistively-driven growth has been reduced considerably in comparison with previous studies [12] by employing a larger reactive (non-dissipating) admittance.

The admittance is defined as $Y = 1/R + i\omega C$, and the dissipated power is

$$\langle P \rangle = \frac{I^2}{2} \text{Re}\{1/Y\} = \frac{I^2}{2} \cdot \frac{R}{1 + (\omega RC)^2}, \qquad (1)$$

where I is the current, C is the capacitance, and ω is the $m = 1$ mode frequency. For $(\omega RC)^2 >> 1$, the dissipated power can be reduced by increasing R and C subject only to a minimum signal level, which is proportional to $1/\omega C$, and the signal offset due to bias currents in the amplifier, which is proportional to R.

To increase the growth rate above this minimum, the wall resistance can be increased simply by connecting the opposite cylinder through a series resistor to ground. For small series resistors, R_s, i.e., $(\omega R_s C)^2 << 1$, the growth rate of the resistive-wall instability increases linearly with R_s [12]. This value is determined empirically by choosing a resistor small enough to avoid forcing the plasma column into the trap wall, yet large enough to observe a reasonable signal.

PRESSURE SENSITIVITY OF THE $m = 1$ DIOCOTRON MODE

As mentioned in the introduction, collisions with neutral particles apply a torque to the plasma, causing it to expand and lose potential energy. Because the diocotron mode amplitude grows at the expense of the plasma's energy, the mode may be stimulated by collisions. A calculation assuming that the expansion of the plasma is sufficiently slow that the radial density profile can be regarded as stationary on the time scale of the instability has predicted a growth rate that scales linearly with neutral pressure [13, 14]. In previous experiments on the EDG device, however, increased background gas pressure resulted in substantial, non-exponential *damping* of the diocotron mode and the the mode duration *decreased* with pressure (scaling as $P^{-1/2}$ in the range from 10^{-9} to 10^{-7} Torr [7]). The assumption of a stationary density profile [13, 14] is likely invalid because the plasma expands on a time scale comparable to the predicted growth time of the instability, however the physical mechanism of the pressure-induced damping is still unexplained.

In the present series of experiments, diocotron mode sensitivity at even lower pressures was investigated under several experimental conditions, including reducing the plasma diameter by employing both 1" and 1/2" diameter filaments. All data were taken in a magnetic field of 600 Gauss and the line density was approximately $2 - 3 \times 10^7$ cm^{-1}. Six neutral helium pressure scans are shown in Fig. 1, one with a neutral pressure as low as 5×10^{-11} Torr. In all cases, the damping rate is strongly sensitive to helium pressures greater than 5×10^{-8} Torr. For three of the scans, the sensitivity at lower pressures was too slight to discern, and for two of the scans, the damping rates increased with pressure approximately as $P^{1/4}$. The discrepancy between the pressure scaling in this experiment and the experiment cited in the previous paragraph [7] is that the present results include the correction for the ion gauge's sensitivity to helium, and the previous data were plotted versus gauge pressure.

The differences in the behavior of the growth rate at low neutral pressure appears to depend mainly on two quantities:
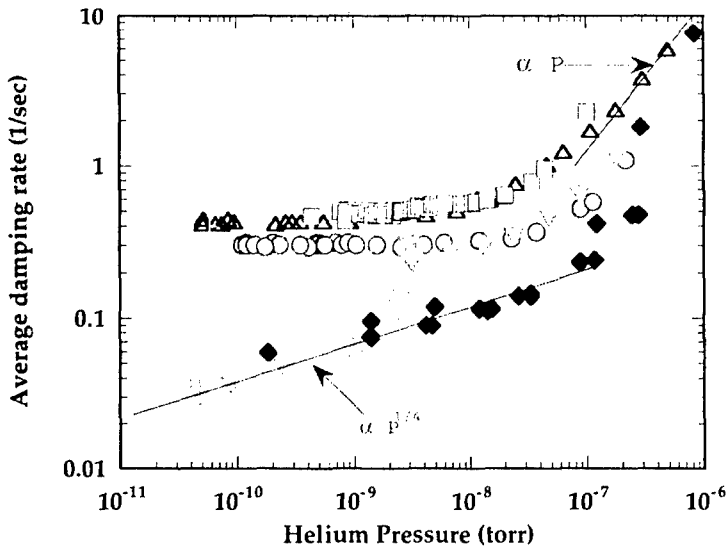
FIGURE 1. Plot of average damping rate of the diocotron mode versus neutral pressure, corrected for the ion gauge's sensitivity to helium in the gas mixture. The open circles are from the 1/2" diameter filament and the other data are from the 1" diameter filament.

1. The initial diocotron mode amplitude, which is controlled by momentarily connecting a cylinder through a series $1k\Omega$ resistor to ground *via* a time-adjustable relay.

2. The net diocotron mode growth rate, which is controlled by balancing the resistive growth against the inherent damping. This mode growth was driven throughout the discharge by connecting one 200 pF trap half-cylinder to ground through a 25Ω resistor. This corresponds to a resistively-driven growth rate of 0.2 - 0.3 sec^{-1}.

For the open squares and triangles in Fig. 1, the mode was resistively grown for about 0.2 seconds and then allowed to damp without further forcing. In this case, the initial amplitude was about 2-3 mm, which is about 10% of the wall radius. Operating in this manner has the advantage of a very nearly exponential decay, i.e., the decay rate is nearly constant and data windowing is not necessary. At pressures above 5×10^{-8} Torr, the damping rate scaled linearly with pressure, but below that, the damping rate was 0.4 sec^{-1} regardless of the pressure. This was repeated with a smaller filament with the expectation that the smaller plasma radius would delay charge loss and other interactions with the trap wall. But, as shown by the open circles, the low-pressure sensitivity was even weaker.

Surmising that the damping due to neutral pressure was being masked by resistively forcing the plasma too far off-axis, scans were performed with smaller initial diocotron mode amplitude. In addition to the reduction in amplitude, the mode *damping rate* was also observed to decrease (by a factor of four at low pressure), as represented by the closed diamonds in Fig. 1. Pressure sensitivity was observed, with the decay rate, γ,

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scaling as $P^{1/4}$ down to about 10^{-9} Torr but the decay was not exponential.

Previous observations [7] revealed that maximum sensitivity to changes in neutral pressure are realized when the net diocotron damping rate is minimized, i.e., the mode is made to last as long as possible. In the scan depicted by both the closed and open inverted triangles in Fig. 1, small values of wall resistance (connected throughout the discharge) were added to drive the mode in order to reduce the net decay rate. This is in contrast to the strong resistive destabilization that was employed only at the very beginning of the discharge. At pressures below 3×10^{-9} Torr (closed inverted triangles), the mode damped initially as before, but then began to grow, as shown in Fig. 2. After 10-20 seconds, the mode peaked and decayed again, but not exponentially. The value of the static resistance was chosen to maximize the mode amplitude but still prevent the plasma from striking the wall and losing charge. The recorded damping rate was the negative of the average growth rate calculated from the time of peak amplitude to the time corresponding to half of the peak amplitude. These modes lasted more than 50 seconds and the decay rate scaled as $P^{1/4}$ (depicted by the closed inverted triangles) down to 5×10^{-11} Torr, the base pressure of the EDG.
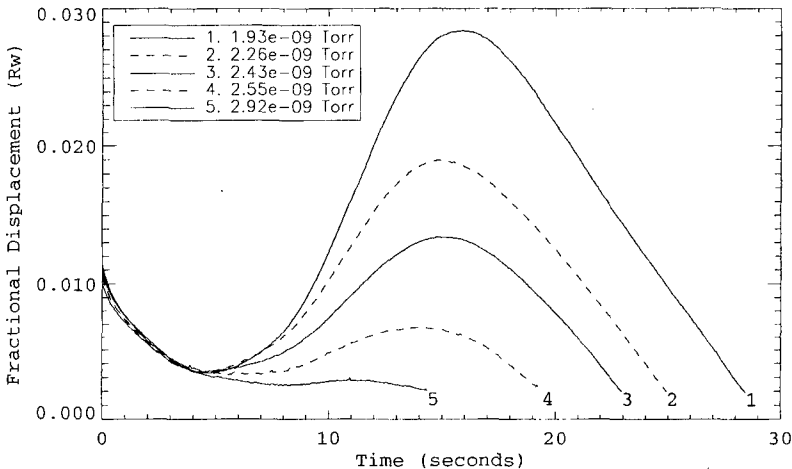

FIGURE 2. Evolution of the mode amplitude in the region of highest sensitivity to pressure. Whereas the pressure varies by about 50%, the damping rate varies by a factor of three. In all the scans at low pressure, the exponential decay (seen here during the first four seconds) is not sensitive to pressure.

For pressures above 3×10^{-9} Torr, the mode did not grow. As shown by the open inverted triangles in Fig. 1, the pure exponential decay was insensitive to pressure in a manner similar to the scan with the strongly forced initial amplitude. The abrupt transition from mode growth to mode damping between 2 and 3×10^{-9} Torr is remarkable because the mode behavior is very sensitive to pressure (approximately P^3). Mode evolutions in this region are shown in Fig. 2. Though unexplained at present, a very sensitive measurement of neutral pressure might be achieved if this behavior can be extended to lower pressure.

Overall, the pressure sensitivity of the diocotron mode damping is very reminiscent of that observed with plasma expansion:

1. At high pressures, the sensitivity to pressure appears to scale linearly with neutral pressure.

2. At low pressures both expansion and mode damping are much less pressure sensitive. Unlike expansion, the mode damping exhibits a weak dependence on pressure.

3. The transition in the pressure sensitivity is at 4×10^{-8} Torr.

4. The faster than linear dependence of mode damping on diocotron mode frequency[12] is similar to the $B^{-3/2}$ dependence of the asymmetry- induced plasma expansion on magnetic field [6].

Qualitatively, at higher pressure, the mode appears to be strongly damped when the plasma expands rapidly due to electron-neutral collisions. At lower pressure it appears to be mildly damped when the plasma is expanding slowly due to asymmetries. There is evidence that damping rate is affected by the plasma expansion but the determination that the expanding plasma is causing mode decay requires further experiments. The mode behavior appears to be determined by a balance between the growth driven by the resistive instability and the damping mechanisms, some of which are observed to be pressure dependent - either directly or coupled through the column expansion. There is likely more than one source of mode damping because of the variability in nature of the damping. When the mode amplitude is grown with a high wall resistance and then allowed to decay on its own, the damping is exponential. The rate of exponential decay is seen to be less with smaller initial amplitude. When the net damping rate is reduced by adding a modest wall resistance, the decay is not exponential. The non-exponential damping is very sensitive to neutral pressure in a narrow pressure range.

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